

# The Weihai Observatory search for close-in planets orbiting giant stars

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## ABSTRACT

Planets are known to orbit giant stars, yet there is a shortage of planets orbiting within  $\sim 0.5$  AU ( $P \lesssim 100$  days). First-ascent giants have not expanded enough to engulf such planets, but tidal forces can bring planets to the surface of the star far beyond the stellar radius. So the question remains: are tidal forces strong enough in these stars to engulf all the missing planets? We describe a high-cadence observational program to obtain precise radial velocities of bright giants from Weihai Observatory of Shandong University. We present data on the planet host Beta Gem (HD 62509), confirming our ability to derive accurate and precise velocities; our data achieve an rms of  $7.3 \text{ m s}^{-1}$  about the Keplerian orbit fit. This planet-search programme currently receives  $\sim 100$  nights per year, allowing us to aggressively pursue short-period planets to determine whether they are truly absent.

*Subject headings:* planetary systems – techniques: radial velocities – stars: giants

## 1. Introduction

Searches for planets orbiting evolved stars have been underway for more than a decade. A major science goal of these campaigns has been to explore the dependence of planetary sys-

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tem properties on host star mass – precise radial velocities can be obtained for these “retired A stars” whereas A-type dwarfs present few absorption lines from which Doppler information can be extracted. However, of the 94 planets known to orbit giant stars ( $\log g < 3.5$ ), only seven have semimajor axes  $a < 0.5$  AU. This is in spite of a strong bias favoring the detection of short-period planets. About 2000 evolved high-mass stars are currently being monitored worldwide by various teams, (Hatzes & Cochran 1993; Frink et al. 2002; Sato et al. 2003; Setiawan et al. 2003; Hatzes et al. 2005; Johnson et al. 2006; Niedzielski & Wolszczan 2008; Lee et al. 2011; Wittenmyer et al. 2011b, e.g.). Given that short-period planets are common around solar-mass stars, there is an open question: Where are the short-period planets around high-mass stars?

Villaver & Livio (2009) proposed that planetary orbits are affected by the evolution of the stars, showing how tidal interaction can lead to the engulfment of close-in planets. This process is strongly influenced by stellar evolution details such as the stellar mass, mass-loss, and metallicity. Engulfment appears to be much more efficient for more-massive planets and less-massive stars (Kunitomo et al. 2011; Villaver et al. 2014).

Giant and subgiant stars sample planet hosts that, in principle, are more massive than their main sequence counterparts (e.g. Johnson et al. 2010; Sato et al. 2008; Bowler et al. 2010; Gettel et al. 2012). This supposition (taken alone) has been used to suggest a relation between planet formation and stellar mass (Currie 2009). We note that the masses of these evolved stars have been the subject of some controversy, e.g. Lloyd (2011, 2013); Johnson et al. (2013). In brief, Lloyd (2011) argues that due to the stellar initial mass function and the rapid evolution of more massive stars, a given evolved star is more likely to be a “retired” Sun-like star than a “retired A star” as put forward by Johnson et al. (2006) and Johnson et al. (2013). While this relation might still hold, there is, however, an increasing number of close-in planets being detected in the main-sequence stage orbiting A-F stars (e.g., HAT-P-49, Bieryla et al. 2014; WTS-1b, Cappetta et al. 2012; Kepler-14b, Buchhave et al. 2011; WASP-33b, Collier Cameron et al. 2010; KELT-3b, Pepper et al. 2013; OGLE2-TR-L9b, Snellen et al. 2009). These close-in planets are not found in radial velocity searches around evolved stars, suggesting that it is the evolution of the star, and not its mass, that plays a major role in removing planets from close orbits. Thus the discovery of a population of short period planets around evolved stars can offer fundamental insights into the strength of the tidal forces. Understanding these tidal forces is critical for producing accurate models of planetary orbits as stars evolve off the main sequence. Furthermore, they can help to shed some light on the dependency of the planet formation process on the stellar mass, with important implications for gas giant planet formation and migration.

In fact, close-in planets are expected to enter the stellar envelope as the star leaves the

main sequence and evolves onto the red giant branch (Villaver & Livio 2009; Villaver et al. 2014). As the star evolves, it removes planets from a region that extends far beyond the stellar radius to the entire region of tidal influence ( $a/R_* \sim 2 - 3$  for a Jupiter-mass planet). During the subgiant phase, the star first clears out the very close-in planets present during the main-sequence evolution, and then proceeds to clear out a larger region as the stellar radius increases when it ascends the red-giant branch. However, the vast majority of the evolved stars targeted by radial-velocity surveys have not completed their ascent up the red-giant branch, and so are not at their maximum radius. The evolved stars currently known to host planets have typical radii smaller than about  $6R_\odot$  (Sato et al. 2010). Stellar evolution models by Villaver & Livio (2009) show that for a  $2M_\odot$  star, the radius exceeds 0.1 AU (i.e. a 10-day orbital period) for only the 40 million years immediately preceding the helium flash. For these reasons, we only expect planets orbiting closer than  $a \sim 0.15$  AU to be lost to their expanding host star, and this only excludes planets with  $P \lesssim 15$  days (Johnson et al. 2007). Our survey will search for the planets with  $15 < P < 100$  days which are common around main-sequence stars, but missing around evolved stars.

This paper is organised as follows: Section 2 describes the Weihai Echelle Spectrograph (WES), and the target selection criteria. Section 3 demonstrates the ability of the WES to deliver precise radial velocities by presenting new data and orbital fits for the known planet-hosting giant Beta Gem (HD 62509). Finally, we give our conclusions in Section 4.

## 2. Observational Program

### 2.1. The Weihai Observatory Echelle Spectrograph

The Weihai Echelle Spectrograph (WES) is a bench-mounted, stabilised, fibre-fed spectrograph attached to the 1-metre telescope located at the Weihai Observatory of Shandong University in Weihai, China. The spectrograph is thermally stabilised to  $\pm 0.10$  K. Light is fed from the telescope into the spectrograph by  $\sim 10$  m of circular fibre with diameter  $70\mu\text{m}$  via a  $160\mu\text{m}$  pinhole. It can achieve a maximum resolution of 57,000 with 2.2-pixel sampling. The WES is the first fibre-fed echelle spectrograph in China, and has the primary function of radial-velocity planet search. Further details about the spectrograph and the Weihai Observatory site can be found in Gao & Ren (2014), Hu et al. (2014), and Guo et al. (2014).

The observing and data analysis procedures are typical of precise radial-velocity planet searches. Doppler velocity observations are performed at a resolving power of  $R \sim 45,000$ . Calibration of the spectrograph point-spread function is achieved using an iodine absorption

cell temperature-controlled at  $65.0 \pm 0.1^\circ\text{C}$ . The iodine cell imprints a dense forest of narrow absorption lines on the stellar spectrum, from 5000 to 6200 Å, permitting the contemporaneous calibration of the spectrograph point-spread function (Valenti et al. 1995; Butler et al. 1996). Velocities are obtained using the *Austral* code (Endl et al. 2000), which has been successfully used by several planet-search programs for more than 10 years (Endl et al. 2004; Wittenmyer et al. 2011b; Robertson et al. 2012a). The iodine region is broken into  $\sim 380$  100-pixel chunks, corresponding to about 4.3 Å per chunk. The chunks are weighted by their Doppler content (defined as the sum of all pixel to pixel gradients), and each chunk produces a radial velocity relative to the iodine-free template spectrum. The final velocity is computed as the mean value of the chunks after an iterative  $3\sigma$  clipping to reject outliers. The uncertainty is the standard error of the mean, i.e. the rms scatter divided by the square root of the number of accepted chunks.

## 2.2. Target selection and observing strategy

We chose a small sample of bright giants, starting with Northern hemisphere *Hipparcos* stars with  $V < 5.0$  and luminosity classes III and IV (van Leeuwen 2007). After removing all stars flagged for variability, double/multiple stars, and suspected composite spectra, we imposed a colour cut  $0.5 < (B - V) < 1.2$  to match the selection criteria of many evolved-star planet-search surveys (e.g. Sato et al. 2005; Johnson et al. 2006; Niedzielski & Wolszczan 2008; Jones et al. 2011). We then required  $M_V > 0.0$  to exclude the most-evolved stars which would be subject to large-scale pulsations that confound radial-velocity searches for planets (Hekker et al. 2008). To reduce the impact of pulsations on the detectability of planets, we also required that the *Hipparcos* photometric scatter be smaller than 0.005 mag. From the scaling relations of Kjeldsen & Bedding (1995), this threshold corresponds to velocity amplitudes smaller than  $5\text{--}10 \text{ m s}^{-1}$ , a level comparable to our photon noise and small compared to the expected amplitudes of giant planets in short-period orbits. The 42 remaining targets are enumerated in Table 1.

Our knowledge of short-period planets orbiting these evolved stars remains limited by the observing strategies employed by the major programs. Radial-velocity surveys are usually subject to the exigencies of telescope scheduling, such that they are typically allocated time in a single short run each month (during the bright lunation). The “Rocky Planet Search” campaigns conducted by the Anglo-Australian Planet Search addressed this problem by observing a subset of  $\sim 30$  stars every night for 48 consecutive nights. Those campaigns have demonstrated dramatically increased sensitivity to short-period planets (O’Toole et al. 2009; Vogt et al. 2010; Wittenmyer et al. 2011a). Clearly, high cadence is the way forward

(Swift et al. 2015). For example, Jones et al. (2015) were able to conclusively detect the 89-day planet orbiting the K giant HD 121056 by densely sampling its orbit using CHIRON, a spectrograph dedicated to precise radial-velocity planet search (Tokovinin et al. 2013). To achieve the best possible cadence, our survey has been allocated  $\sim 100$  nights per year on the Weihai Observatory 1m telescope.

### 3. Preliminary Results: Beta Gem’s Planetary Companion

Six of our 42 targets are known planet hosts (Table 2). They are useful members of the sample because (1) further monitoring can often reveal additional planets (Wright et al. 2009; Wittenmyer et al. 2013), and (2) the repository of data on these systems can serve as a check on the new data being obtained by this survey.

Beta Gem (HD 62509, HIP 37826) is an extremely bright K0 giant ( $V = 1.14$ ) known to host a planet with  $P = 590$  days and  $m \sin i = 2.76 M_{\text{Jup}}$  (Hatzes & Cochran 1993; Hatzes et al. 2006). We have 38 observations of HD 62509 over a 500-day baseline, with a mean internal velocity uncertainty of  $8.6 \text{ m s}^{-1}$ . Exposure times ranged from 300-900 seconds, with typical  $S/N \sim 200$ -300 per pixel. An iodine-free template spectrum was obtained on 2014 March 7, and all velocities given in Table 3 are computed relative to that template.

To check the consistency of the Weihai data, we include all published velocities spanning more than 25 years to fit a Keplerian orbit to the planetary signal. Our analysis uses eight data sets, seven of which have already been published. Larson et al. (1993) presented velocities from the CFHT ( $N = 39$ ) and DAO ( $N = 27$ ), calibrated using an HF gas cell (Campbell & Walker 1979), a precursor to the currently-used iodine cell technique. The Beta Gem planet discovery paper (Hatzes & Cochran 1993) gave 38 radial-velocity measurements from the McDonald Observatory 2.1m telescope. Hatzes et al. (2006) reported a further 22 epochs from the ongoing McDonald Observatory 2.7m “Phase 3” planet-search (e.g. Robertson et al. 2012a,b) and 11 epochs using a higher-resolution, limited wavelength setting on the same telescope (“cs21” as described in Hatzes et al. 2006 and Wittenmyer et al. 2006). The Tautenburg Observatory Planet Search (TOPS) also yielded 22 radial velocities as presented in Hatzes et al. (2006). Finally, 80 velocities from Lick Observatory given in Reffert et al. (2006) were included in our fit.

We used the *GaussFit* nonlinear least-squares code (Jefferys et al. 1987) to obtain a Keplerian model fit for all eight data sets simultaneously. The velocity data now span 33.5 years. Uncertainties were estimated using the bootstrap routine within *Systemic 2* (Meschiari et al. 2009) on 10,000 synthetic data set realisations. The results are given in

Table 4, and the most recent cycles including the Weihai data are plotted in Figure 1. The rms about the fit for the Weihai velocities is  $7.3 \text{ ms}^{-1}$ , comparable to the previously published data, and consistent with the stellar oscillation amplitude of  $5\text{--}6 \text{ ms}^{-1}$  found by Hatzes et al. (2012). This result demonstrates that the Weihai data acquisition and Doppler velocity extraction techniques are robust.

#### 4. Summary and Conclusions

Close-in planets ( $a < 0.5 \text{ AU}$ ,  $P \lesssim 100 \text{ days}$ ) are rare around giant-branch stars. We have begun an observational program at the 1m telescope located at Weihai Observatory of Shandong University, using its stabilised echelle spectrograph to obtain precise Doppler velocity measurements of a sample of bright giant stars. We aim to observe these stars with as high a cadence as possible to search for these “missing” planets. Preliminary results from this program give excellent results for the known planet-host Beta Gem (HD 62509), and confirm our ability to obtain precise velocities with this new instrument.

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Table 1. Weihai target list

HIP	HD	RA	Dec	$V$	$T_{eff}$ (K)	$\log g$ (cgs)	[Fe/H]	Reference
3031	3546	00 38 33.50	+29 18 44.5	4.34	5102	2.80	-0.56	Luck & Heiter (2007)
4422	5395	00 56 40.01	+59 10 52.2	4.62	4875	2.7	-0.51	Massarotti et al. (2008)
4906	6186	01 02 56.66	+07 53 24.3	4.27	4955	2.68	-0.24	Luck & Heiter (2007)
5586	7106	01 11 39.59	+30 05 23.0	4.51	4748	2.62	0.01	Luck & Heiter (2007)
6411	8207	01 22 20.39	+45 31 43.5	4.87	4656	2.8	0.03	Massarotti et al. (2008)
7294	9408	01 33 55.93	+59 13 55.5	4.68	4900	2.67	-0.22	Luck & Heiter (2007)
9884	12929	02 07 10.29	+23 27 46.0	2.01	4498	2.4	-0.25	Massarotti et al. (2008)
13061	17361	02 47 54.44	+29 14 50.7	4.52	4727	2.67	0.07	Luck & Heiter (2007)
14668	19476	03 09 29.63	+44 51 28.4	3.79	5022	3.12	0.19	Luck & Heiter (2007)
14838	19787	03 11 37.67	+19 43 36.1	4.35	4732	2.7	-0.03	Massarotti et al. (2008)
19038	25604	04 04 41.66	+22 04 55.4	4.36	4699	2.6	0.01	Massarotti et al. (2008)
20252	27348	04 20 24.66	+34 34 00.3	4.93	5073	3.10	0.09	Luck & Heiter (2007)
20455	27697	04 22 56.03	+17 32 33.3	3.77	5058	3.02	0.19	Luck & Heiter (2007)
20877	28292	04 28 26.37	+16 21 34.7	4.96	4529	2.5	-0.17	Massarotti et al. (2008)
20885	28307	04 28 34.43	+15 57 44.0	3.84	4955	2.9	0.04	Massarotti et al. (2008)
20889	28305	04 28 36.93	+19 10 49.9	3.53	4797	2.6	0.04	Massarotti et al. (2008)
22957	31421	04 56 22.32	+13 30 52.5	4.06	4498	2.4	-0.26	Massarotti et al. (2008)
24822	34559	05 19 16.59	+22 05 48.1	4.96	5096	3.17	0.10	Luck & Heiter (2007)
26366	37160	05 36 54.33	+09 17 29.1	4.09	4898	2.9	-0.63	Massarotti et al. (2008)
26885	37984	05 42 28.66	+01 28 28.8	4.90	4508	2.2	-0.55	Massarotti et al. (2008)
27483	38656	05 49 10.46	+39 10 52.1	4.51	5021	2.90	-0.09	Luck & Heiter (2007)
28358	40035	05 59 31.55	+54 17 05.9	3.72	4911	2.86	-0.01	Luck & Heiter (2007)
29696	43039	06 15 22.74	+29 29 55.4	4.32	4732	2.7	-0.33	Massarotti et al. (2008)
37740	62345	07 44 26.87	+24 23 53.3	3.57	5101	3.04	0.03	Luck & Heiter (2007)
37826	62509	07 45 19.36	+28 01 34.7	1.16	4998	3.13	0.17	Luck & Heiter (2007)
39424	66216	08 03 31.10	+27 47 39.9	4.94	4560	2.5	0.03	Massarotti et al. (2008)
42527	73108	08 40 12.90	+64 19 40.3	4.59	4564	2.28	-0.16	Luck & Heiter (2007)
42911	74442	08 44 41.11	+18 09 17.5	3.94	4763	2.67	0.01	Luck & Heiter (2007)
47029	82741	09 35 03.85	+39 37 17.2	4.81	4934	2.81	-0.12	Luck & Heiter (2007)
51808	91190	10 35 05.59	+75 42 46.7	4.86	4890	3.07	-0.15	McWilliam (1990)
53229	94264	10 53 18.64	+34 12 56.0	3.79	4677	2.8	-0.20	Massarotti et al. (2008)
58948	104979	12 05 12.67	+08 43 58.2	4.12	4996	2.86	-0.33	Luck & Heiter (2007)
59847	106714	12 16 20.56	+23 56 43.5	4.93	4887	2.6	-0.24	Massarotti et al. (2008)
60172	107328	12 20 21.15	+03 18 45.8	4.97	4514	1.94	-0.46	Luck & Heiter (2007)
62763	111812	12 51 41.93	+27 32 26.6	4.93	5623	2.9	0.01	Massarotti et al. (2008)
63608	113226	13 02 10.76	+10 57 32.8	2.85	5145	3.12	0.13	Luck & Heiter (2007)
72125	129972	14 45 14.50	+16 57 51.9	4.60	4887	2.7	-0.10	Massarotti et al. (2008)
73620	133165	15 02 54.07	+02 05 28.6	4.39	4825	2.79	-0.13	Luck & Heiter (2007)
74666	135722	15 15 30.10	+33 18 54.4	3.46	4963	2.73	-0.30	Luck & Heiter (2007)
75458	137759	15 24 55.78	+58 57 57.7	3.29	4477	2.5	0.03	Massarotti et al. (2008)
77070	140573	15 44 16.00	+06 25 31.9	2.63	4498	2.5	0.03	Massarotti et al. (2008)
77655	142091	15 51 13.94	+35 39 29.6	4.79	4764	3.0	-0.04	Massarotti et al. (2008)

Table 2. Known Planet Hosts in the WES Sample

Planet	Period (days)	$M \sin i$ ( $M_{\text{Jup}}$ )	$a$ (AU)	Reference
$\alpha$ Ari (HD 12929)	$380.0 \pm 0.3$	$1.72 \pm 0.19$	$1.130 \pm 0.062$	Lee et al. (2011)
$\epsilon$ Tau (HD 28305)	$595 \pm 5$	$7.7 \pm 0.3$	$1.936 \pm 0.034$	Sato et al. (2007)
$\beta$ Gem (HD 62509)	$589.6 \pm 0.8$	$2.76 \pm 0.14$	$1.757 \pm 0.029$	Hatzes & Cochran (1993)
4 UMa (HD 73108)	$269 \pm 2$	$7.1 \pm 0.6$	$0.877 \pm 0.036$	Döllinger et al. (2007)
$\iota$ Dra (HD 137759)	$511.098 \pm 0.089$	$9.3 \pm 0.9$	$1.31 \pm 0.06$	Frink et al. (2002)
$\kappa$ CrB (HD 142091)	$1300 \pm 15$	$1.97 \pm 0.12$	$2.72 \pm 0.05$	Johnson et al. (2008)

Table 3. Weihai radial velocities for HD 62509

BJD-2400000	Velocity ( $\text{m s}^{-1}$ )	Uncertainty ( $\text{m s}^{-1}$ )
56293.24524	-9.0	7.7
56293.25392	-6.1	7.9
56293.26226	-0.3	7.9
56293.27088	-7.5	7.4
56316.09065	-11.9	8.4
56316.10066	-2.0	7.9
56316.11256	-13.7	8.2
56316.12067	-2.4	8.6
56316.12989	-12.9	8.2
56317.12107	-6.8	7.2
56317.13220	-3.0	7.8
56320.13640	-16.6	8.0
56320.14513	-12.8	8.4
56320.15348	-11.7	8.1
56320.16399	-11.6	8.5
56320.17287	2.6	8.7
56617.27237	73.8	9.2
56617.28150	72.2	8.9
56617.28955	72.6	9.0
56617.29755	74.0	9.1
56617.30750	83.4	9.1
56617.31558	84.1	9.9
56617.32360	81.1	8.7
56617.33160	82.5	8.9
56617.34040	79.5	9.4
56617.34844	79.0	9.4
56724.03493	43.2	10.2
56749.01689	46.8	8.1
56749.04009	48.4	8.7
56749.07138	43.2	8.1
56763.99622	40.0	7.8
56764.02025	46.0	8.3
56781.98304	27.1	8.6
56781.99446	31.3	8.6
56782.03382	2.5	8.4
56786.99866	32.3	8.2
56792.98783	13.2	9.5
56792.99932	37.6	10.8

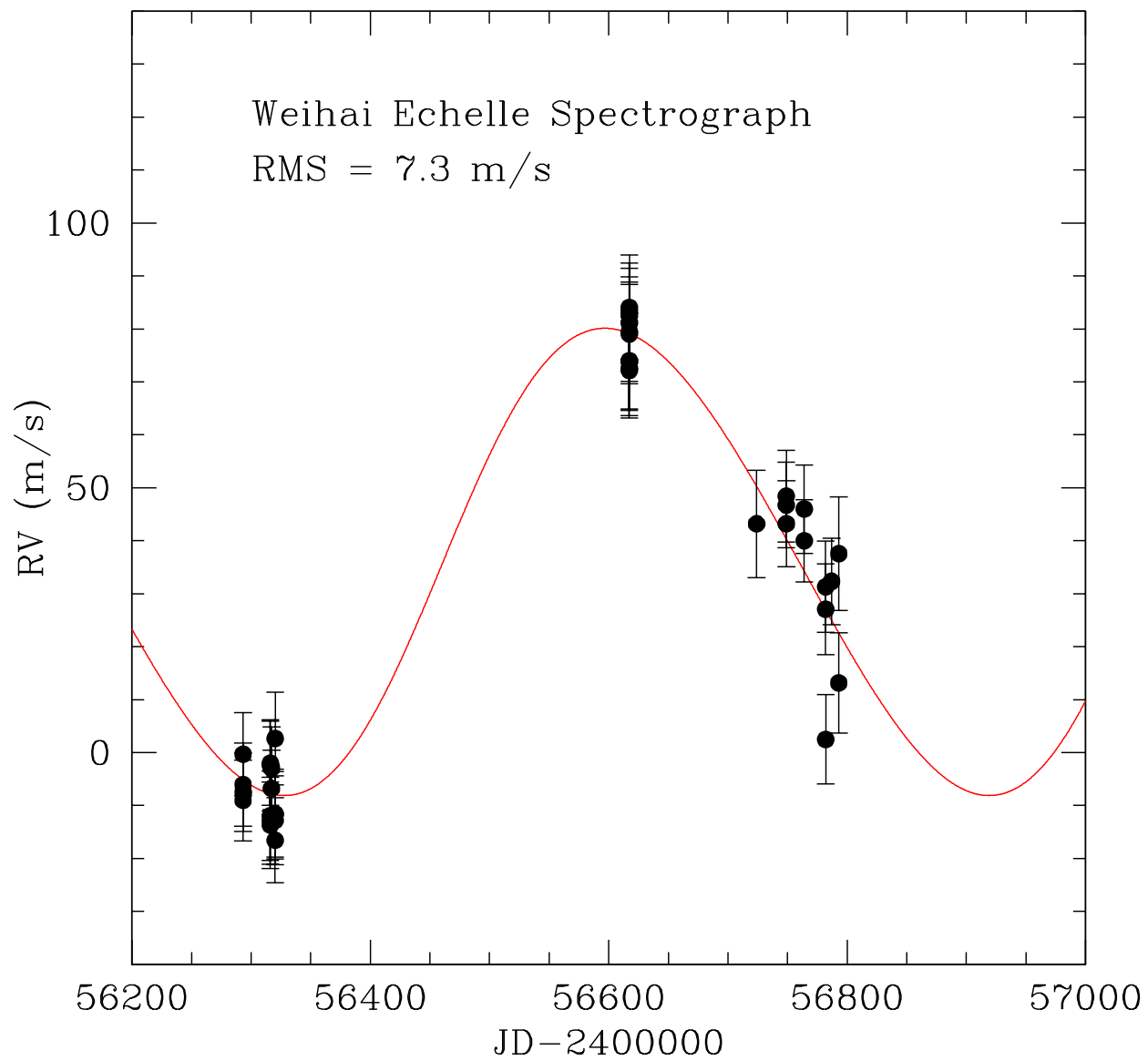


Fig. 1.— WES data for Beta Gem: 38 observations from 2013 Dec 31 to 2014 May 15. Our results are in excellent agreement with the published data, now spanning 33.5 years and confirming the consistency of the planet’s orbital parameters.

Table 4. Updated Parameters for HD 62509b

Parameter	Value
Period	$591.2 \pm 0.76$ days
Eccentricity	$0.071 \pm 0.028$
$\omega$	$263 \pm 19$ degrees
$K$ ( $\text{m s}^{-1}$ )	$44.1 \pm 1.2$ $\text{m s}^{-1}$
$T_0$	$2444036.3 \pm 32.5$ JD
$m \sin i$	$2.80 \pm 0.08$ $M_{\text{Jup}}$
$a$	$1.7113 \pm 0.0015$ AU
RMS – McD cs21	$14.9 \text{ m s}^{-1}$
RMS – McD phase 3	$13.7 \text{ m s}^{-1}$
RMS – TOPS	$12.0 \text{ m s}^{-1}$
RMS – CFHT	$19.2 \text{ m s}^{-1}$
RMS – DAO	$37.2 \text{ m s}^{-1}$
RMS – McD 2.1m	$23.2 \text{ m s}^{-1}$
RMS – Lick	$9.2 \text{ m s}^{-1}$
RMS – Weihai	$7.3 \text{ m s}^{-1}$